9 Changes in Open Space and Vegetation

Stormwater management practices that use vegetated areas to filter and slow stormwater runoff provide both direct stormwater management benefits for receiving waters, and ancillary land-based benefits from increasing vegetative cover and open space. Relative to conventional development practices, the ancillary benefits of vegetation-based practices include ecosystem services like improved upland wildlife habitat, air pollution removal, greenhouse gas mitigation, heat island mitigation, enhanced property values, aesthetic improvements, and others (Chapter X provides more detail).

EPA projects that the three policy scenarios described in Chapter X will increase vegetation as development sites are redesigned to replace impervious cover with vegetated areas. EPA analyzed two pathways by which increasing vegetation levels in developed areas can reduce ambient concentrations of criteria air pollutants: directly, by removing pollutants from the air, and indirectly, by reducing air emissions associated with energy use for cooling and heating buildings.

The level of atmospheric pollutant removal services provided by vegetation under the three policy scenarios depends in part on the nature and amount of additional vegetation beyond baseline conditions expected under each of the policy scenarios. This Chapter describes the data, methodology, and assumptions that EPA used to quantify changes in vegetation for its analysis of air pollution removal services and its carbon sequestration analysis.

9.1 Estimate Changes in Vegetation

EPA's analysis of benefits from an increase in vegetative cover focuses on development projects managing stormwater through the use of site redesign to replace impervious surfaces with vegetated areas. [redacted]

[redacted]

Table 1-1: National Summary of Impervious Cover (IC) in 2040 by Policy Scenario

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

[redacted]

Table 1-2: Summary of Average Changes in Impervious Cover (IC) within Analyzed HUC12 Watersheds in 2040 by Policy Scenario			
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]			

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

$$[redacted]\, n\, [redacted]\, [redacted] \quad [redacted]$$

$$[redacted]\, n\, [redacted]\, [redacted]\, [redacted]\, G\, [redacted] \quad [redacted]$$

[redacted]

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[redacted] [redacted]

[redacted] [redacted]

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3 [redacted]

10 Carbon Sequestration

Climate change is widely viewed to be a significant long-term threat to the global environment. Carbon dioxide (CO_2) and other greenhouse gases (e.g., CH_4 and N_2O) contribute to climate change by absorbing outgoing terrestrial radiation (Jo & McPherson, 2001; U.S. EPA, 2010). EPA projects that the three policy scenarios described in Chapter X will increase vegetation as development sites are redesigned to replace impervious cover with vegetated areas. EPA analyzed how increasing vegetation levels in developed areas can reduce atmospheric carbon (C) in two ways: directly, by sequestering and storing carbon and indirectly, by reducing building energy use (Akbari & Konopacki, 2003; Jo & McPherson, 1995).

Trees and other vegetation sequester carbon in their biomass or in the soil, removing it from the atmosphere and preventing it from contributing to climate change. EPA quantified the amount of carbon sequestered annually by trees and grass by applying values for carbon sequestration per unit area to the amount of additional vegetation in each year of the analysis. [redacted]

This chapter focuses on the economic benefits of greenhouse gas mitigation from carbon sequestration by vegetation. EPA monetized the economic benefits of sequestration based on the social cost of carbon (SCC) (Interagency Working Group, 2013). First it describes EPA's method for quantifying changes in vegetation under the policy options, then describes the calculation of net changes in sequestration and estimation of monetary benefits. Chapter X of this report presents EPA's analysis of reduced greenhouse gas emissions resulting from changes in energy consumption for cooling and heating due to shade trees.

10.1 Methodology

EPA's analysis of carbon sequestration under the three policy scenarios has three main steps:

1. *Estimate changes in vegetation under policy scenarios considered (Chapter 1);*
2. *Estimate net changes in carbon sequestration; and*
3. *Estimate monetary benefits based on SCC.*

See Chapter X for descriptions of the estimates of future development, associated stormwater control practices, and the three policy scenarios that EPA used to inform this benefits analysis.

10.1.1 Net Changes in Carbon Sequestration Services

[redacted]

[redacted]

[redacted]

Above-ground herbaceous biomass tends to die annually unlike the woody portions of plants which can store carbon for many years prior to dying and decomposing (Gorte, 2009). Carbon accumulates in the upper soil layers as dead vegetation is added to the surface and decomposes. Carbon can also be injected into the soil through root biomass growth and decomposition. Table 1-4 summarizes annual net carbon sequestration rates for grass cover from the literature. [redacted]

Grasses have been shown to sequester carbon over long periods of time, up to 45 years, with rates greatest in the first 25 to 30 years after establishment of grass cover (W. M. Post & Kwon, 2000; Pouyat, Yesilonis, & Golubiewski, 2009; Qian & Follett, 2002). [redacted]

Table 1-1: Summary of Annual Grass Net Carbon Sequestration Rates from the Literature

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]
	[redacted]	[redacted]
[redacted]		[redacted]
[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

[redacted]

C [redacted]

[redacted]

[redacted]

10.1.2 Estimation of Carbon Sequestration Benefits under Policy scenarios

[redacted] "SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year" (Interagency Working Group, 2013 , p.2). SCC intends to reflect the value of the various effects of climate change, such as changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services affected by climate change. It is typically expressed as dollars per metric ton of carbon dioxide (CO_2) removed from the atmosphere or alternatively as dollars per metric ton of carbon (C). SCC increases over time as incremental damages associated with CO_2 emissions grow (IWG, 2010, 2013).

The economic literature includes many SCC values estimated using various models and assumptions. SCC is often estimated based on outputs from integrated assessment models (IAMs) which tie climate changes to economic damages. Beginning in 2009, EPA has participated in a U.S. Government Interagency Working Group to develop SCC values for use in regulatory analysis (IWG, 2010).[4] The working group developed a set of recommended SCC values for use in U.S. regulatory analyses based on the average from original runs of three IAMs – the Dynamic Integrated Climate and Economy model (DICE), the Policy Analysis of the Greenhouse Effects model (PAGE), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model (IWG, 2010). A technical update to the SCC values was released in 2013 (IWG, 2010).

The discounting of SCC values requires special consideration because of the discount rate assumptions included within their estimation. That is, an SCC value estimated for a given year reflects costs in later years which are discounted back to the year when the CO_2 is emitted. The Interagency Working Group selected four sets of SCC values for use in regulatory analysis, using 2.5 percent, 3 percent, and 5 percent discount rates. The fourth set of SCC values reflects the 95th percentile SCC values across all models using a 3 percent discount rate. [redacted][5]

[4] Other participants include the Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of Transportation, National Economic Council, Office of Energy and Climate Change, Office of Management and Budget, Office of Science and Technology Policy, and the Department of the Treasury.

[5] Some analysts of SCC have included "equity weights" to account for differences in consumption and relative reductions in wealth across different regions of the world. The argument is that a monetary loss in a poor county results in a greater loss of utility than the same amount of money in a wealthy country. The Interagency Working Group concluded that this approach is not appropriate when estimating SCC values for domestic regulations (IWG, 2010), [redacted].

Table 1-2: SCC Values for 2020 to 2040 (2011$ per metric ton of CO_2)[a]				
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

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- [redacted]
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[redacted]

[redacted]

[redacted]

[redacted]

10.2 Results

[redacted]

Table 1-3: Average Annual Net Carbon Sequestration over the Analysis Period (2020-2040)						
[redacted]	[redacted]					
		[redacted]		[redacted]		[redacted]
[redacted]		[redacted]		[redacted]		[redacted]
[redacted]		[redacted]		[redacted]		[redacted]
[redacted]		[redacted]		[redacted]		[redacted]
[redacted]						

Table 1-4: Annualized Carbon Sequestration Benefits by Regulatory Scenairo (2011$; in millions)

[redacted]	[redacted]	[redacted]		
		[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

10.3 Uncertainty and Limitations

Uncertainty and limitations inherent in EPA's methodology are described below in Table 1-8.

Table 1-5: Uncertainties and Limitations of EPA's Analysis of Carbon Sequestration Benefits

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]

Table 1-5: Uncertainties and Limitations of EPA's Analysis of Carbon Sequestration Benefits		
[redacted]	[redacted]	[redacted]
		[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

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11 Atmospheric Pollutant Removal

Vegetation can act as a sink for ambient pollutants through dry deposition onto the vegetation surface and through uptake through leaf stomata (Beckett, Freer-Smith, & Taylor, 2000; Nowak, Crane, & Stevens, 2006; Yang, Yu, & Gong, 2008; Nowak et al., 2013). "'Dry deposition' describes the combined removal of particulate pollutants from the atmosphere by gravity, Brownian motion, impaction and direct interception" (Beckett, et al., 2000, p.996). Gaseous pollutants are primarily removed by uptake through leaf stomata and particulate pollutants are primarily removed by plant surfaces (Nowak, Crane, et al., 2006; Nowak, et al., 1998). Vegetation is typically only a temporary retention site for particulate pollutants. Intercepted particles are re-suspended into the atmosphere, washed off by precipitation, or deposited on the ground with leaves, twigs, and other plant debris (Nowak, et al., 1998). The mass of pollutant removed by vegetation tends to represent a small fraction of total ambient pollution (Nowak et al. 2006; Nowak et al. 2013). For example, annual percentage reductions in ambient PM2.5 range from 0.05 percent to 0.24 percent for 10 cities examined by Nowak et al. (2013). However, the human health benefits of even small percentage changes in air quality can be substantial (Nowak et al. 2013). [redacted]

This chapter describes EPA's analysis of direct removal of pollutants. [redacted]

11.1 Methodology

EPA's analysis of atmospheric pollutant removal due to the policy options has three main steps:

1. *Estimate changes in vegetation under policy scenarios considered;*
2. *Estimate net reductions in atmospheric pollutant concentrations; and*
3. *Estimate human health benefits from reductions in pollution concentrations.*

See Chapter X for descriptions of the estimates of future development, associated stormwater control practices, and the three policy scenarios that EPA used to inform this benefits analysis. See Chapter 1 for a description of EPA's method for estimating changes in vegetation.

11.1.1 Estimate Net Reductions in Atmospheric Pollutant Concentrations

[redacted]

- [redacted]
- [redacted]

6 [redacted]

[redacted]

The following subsections describe EPA's approach for estimating pollutant removal by tree canopy and grass, and estimating changes in pollutant removal and changes in ambient concentrations under policy scenarios.

11.1.1.1 Tree Canopy Flux Rates for PM_{10}, O_3, SO_2, NO_2, and CO

[redacted]

[redacted] [redacted] [redacted]

[redacted]

[redacted]

[redacted]

7 [redacted]

8 [redacted]

[redacted]

11.1.1.2 Tree Canopy Flux Rates for $PM_{2.5}$

The i-Tree Vue model does not currently include $PM_{2.5}$ flux rates, but USFS has recently published a methodology for estimating $PM_{2.5}$ flux and associated health benefits. The study estimates $PM_{2.5}$ flux rates, effect on ambient $PM_{2.5}$ concentrations, and human health effects for existing tree canopy in ten U.S. cities. It uses hourly weather data and data from the literature to incorporate the effects of windspeed and precipitation on the deposition and resuspension of $PM_{2.5}$. Table 2-1 presents flux rates, changes in concentration, and percent changes in concentrations for the ten cities analyzed by Nowak et al. (2013).

[redacted]

[redacted]

10 USFS derived the state pollutant flux rates in i-Tree Vue from a study of national pollutant removal by Nowak et al. (2006) for the year 1994. USFS adjusted the 1994 flux rates to 2000 based on average regional pollution concentrations from between 1994 and 2000. The i-Tree Vue manual (USFS, 2011) provides additional detail.

[redacted]

Table 2-1: Flux Rates and Calculated Deposition Velocities for Cities Analyzed by Nowak et al. (2013)				
City	Flux Rate ($g\ m^{-2}\ yr^{-1}$)	Change in Concentrations	Percent Change in Concentrations	[redacted]
Atlanta, GA	0.36	0.030	0.24%	[redacted]
Baltimore, MD	0.24	0.010	0.09%	
Boston, MA	0.32	0.020	0.19%	
Chicago, IL	0.26	0.011	0.09%	
Los Angeles, CA	0.13	0.009	0.07%	
Minneapolis, MN	0.23	0.010	0.08%	
New York, NY	0.24	0.010	0.09%	
Philadelphia, PA	0.17	0.006	0.08%	
San Francisco, CA	0.29	0.006	0.05%	
Syracuse, CA	0.27	0.009	0.10%	
[redacted]				
Source: Nowak et al. (2013)				

11.1.1.3 Grass flux rates

[redacted] The i-Tree Vue model and Nowak et al. (2013) do not provide pollutant flux rates for grass. [redacted]

Yang et al. (2008) used a dry deposition model to estimate removal of SO_2, NO_2, PM_{10}, and O_3 by green roofs in Chicago that incorporate short grasses and deciduous trees in their design. To calculate deposition velocity, Yang et al. (2008) assigned resistance components for grass and deciduous trees using algorithms from the literature. Table 2-2 presents estimated flux rates from Yang et al. (2008) for these vegetation types. [redacted]

Table 2-2: Flux Rates Reported by Yang et al. (2008) by Vegetation Type ($g/m^2/yr$)[a]		
Pollutant	Short Grass	Deciduous Trees
SO_2	0.65	1.01
NO_2	2.33	3.57
PM_{10}	1.12	2.16
O_3	4.49	7.17
Total	8.59	13.91
[a] The study also estimated flux rates for herbaceous vegetation. *Source: Yang et al. (2008)*		

[redacted]

[redacted] (2-2)

[redacted]

11.1.1.4 Calculation of Pollutant Removal under Policy Scenarios

[redacted]

Table 2-3: Mean and Standard Deviation of Annual Air Pollutant Flux Rates by Vegetation Type across All Analyzed HUC12 Watersheds

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

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11.1.1.5 Calculation of Changes in Pollutant Concentrations

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11.1.1.6 Calculation of Baseline Pollutant Concentrations

[redacted]

[redacted]

Table 2-4: Average and Standard Deviation of Baseline Pollutant Concentrations for All Analyzed HUC12 Watersheds		
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]		

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11.1.2 Estimation of Human Health Impacts of Air Pollutant Removal

[redacted]

11.1.2.1 Selection of Air Pollutants and Concentration-Response Functions

[redacted]

[redacted]

[redacted]

11.1.2.2 Estimation of Avoided Cases of Each Adverse Health Effect

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18 [redacted]

Table 2-5: Summary of Studies and Concentration-Response Functions Used to Estimate O_3-Related Benefits

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	

[redacted]

11.1.2.3 Valuing Avoided Cases of Adverse Health Effects

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Table 2-6: Unit Values for Several Adverse Health Effects in 2020 and 2040 (in 2011$)[a]				
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11.1.2.4 Annualizing the Present Value of Benefits

[redacted]

11.2 Results

This section summarizes pollutant removal and associated benefits under three policy scenarios. [redacted]

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Table 2-10: Average Mass of Pollutants Removed Annually per Analyzed HUC12 Watershed Over the Analysis Period (kilograms)

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	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 2-11: Average Reduction in Concentrations Over the Analysis Period across All Analyzed HUC12 Watersheds

[redacted]	[redacted]					
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 2-72: Cumulative Avoided Health Incidences from $PM_{2.5}$ Reductions by Policy Scenario, Health Effect, and Year for All Analyzed HUC12 Watersheds[a,b]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 2-72: Cumulative Avoided Health Incidences from $PM_{2.5}$ Reductions by Policy Scenario, Health Effect, and Year for All Analyzed HUC12 Watersheds[a,b]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 2-83: Annualized Health Benefits from $PM_{2.5}$ Reductions by Policy Scenario and Discount Rate for All Analyzed HUC12 Watersheds (in 2011$)[a,b]

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Table 2-94: Avoided Cumulative Health Incidences from O_3 Reductions by Policy Scenario, Health Effect, and Year for All Analyzed HUC12 Watersheds[a]					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 2-5: Annualized Health Benefits from O_3 Reductions by Policy Scenario and Discount Rate for All Analyzed HUC12 Watersheds (in 2011$)[a,b]

[redacted]	[redacted]	[redacted]	[redacted]
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Table 2-106: Annualized Benefits for Reductions in $PM_{2.5}$ and O_3 by Policy Scenario, and Discount Rate for All Analyzed HUC12 Watersheds (2011$; in millions)

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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11.3 Uncertainty and Limitations

Table 2-15 below describes uncertainty and limitations inherent in EPA's methodology for the removal of atmospheric pollutants by vegetation.

Table 2-17: Uncertainties and Limitations of EPA's Analysis of Atmospheric Pollutant Removal by Vegetation

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Table 2-17: Uncertainties and Limitations of EPA's Analysis of Atmospheric Pollutant Removal by Vegetation

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Table 2-17: Uncertainties and Limitations of EPA's Analysis of Atmospheric Pollutant Removal by Vegetation		
[redacted]	[redacted]	[redacted]
		[redacted]

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Appendix A. Supplementary material to Chapter 2, Carbon Sequestration.

Table 4-1: Annual Net Carbon Sequestration per Unit of Tree Cover Area

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 4-1: Annual Net Carbon Sequestration per Unit of Tree Cover Area

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

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Appendix B: Additional Detail, $PM_{2.5}$ Health Benefits Estimation

This Appendix provides supplementary material to Chapter 3, Atmospheric Pollutant Removal. [redacted]

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Table 88-1: Summary of Studies and Concentration-Response Functions Used to Estimate PM$_{2.5}$-Related Benefits

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